THE USE OF A HIGH-ENERGY K_L^o BEAM TO STUDY $K_L^o + P \rightarrow P + K_S^o$ REGENERATION TO CHECK THE POMERANCHUK THEOREM

J. H. Smith and A. Wattenberg
University of Illinois

July 11, 1968

SUMMARY

Several high-energy K_L^o experiments were considered; the most interesting possibility of a sensitive check of the Pomeranchuk (total cross section) theorem was investigated in detail. The regeneration amplitude depends on the difference in the K^oP and $\bar{K}^oP$ cross section. By looking at the size of the oscillatory interference between the regeneration amplitude and the CP-violating $K_L^o \rightarrow \pi^+\pi^-$ amplitude, one could determine a difference in the particle–antiparticle cross sections to the order of 0.1% at 100 GeV. If the Pomeranchuk theorem limit is not being approached and the cross-section difference is much larger the experiment allows one to study the high-energy behavior of the ω trajectory.

These studies have led to the conclusion that at least two neutral beams should be set up; specifically, the beam which is good for high-energy neutrons gives rise to a very serious neutron background in K_L^o experiments. Therefore, although the best neutron beam is close to 0 mrad the optimum beam for high-energy K_L^o experiments ($\approx$ 100 GeV) should be between 7 to 10 mrad.

The background production of K_S^o in a beam of K_L^o and neutrons

prevents the simple observation of $K_S^o \to \pi^+\pi^-$ in the forward direction from being interpreted as regeneration. One must measure both the interference term and the dependence on target length to separate the background K_S^o production from the regeneration.

The characteristics of the beam and of the detecting apparatus have been described by J. H. Smith in reports B.4-68-17 and B.4-68-106.

Introduction

This report deals with a detailed analysis of a fundamental regeneration experiment using a high-energy K_L^o beam. However, we wish to point out that there are other interesting strong interaction experiments that people will want to perform with a high-energy K_L^o beam. For example,

$$K_L^o + P \begin{array}{l} \nearrow \; P + K^{o*} \\ \searrow \; P + \bar{K}^{o*} \end{array}$$

$$K^{o*} \to K^+ + \pi^-,$$

$$\bar{K}^{o*} \to K^- + \pi^+.$$

At high energies these two reactions should have the same rates and the K_L^o is (to a few tenths of a percent) an equal mixture of K^o and $\bar{K}^o$. One would need to observe the protons as well as the two charged particles.

Other experiments of possible interest are the backward scattering of K^o_L, the backward regeneration of K^o_S, and a search for the coherent production of more massive particles with the same properties and quantum numbers as the K^o_L.

The remainder of this report deals with the $K^o_L + P \rightarrow K^o_S + P$ by coherent regeneration. The regeneration can be easily performed on complex nuclei also; however the interpretation of the results would involve nuclear theory.

Motivation for the Study of $K^o_L + P \rightarrow K^o_S + P$

The coherent regeneration of $K^o_L \rightarrow K^o_S$ on protons at high energies offers a very sensitive way to test the Pomeranchuk Theorem that total cross sections for particles and antiparticles should be equal at high energies. The amplitude for regeneration is proportional to the difference of the forward scattering amplitudes for K^oP and $\bar{K}^oP$. By the optical theorem the imaginary part of the forward-scattering amplitude is proportional to the total cross section. Therefore, if there is a difference in the total cross sections of K^o and $\bar{K}^o$, one will find that there is regeneration. (There is the possibility of an exceptional case when the real parts are different and the imaginary parts are the same; however, the general belief is that the real and imaginary parts are proportional, or that the real part became negligible.) The sensitivity obtainable allows one to observe a difference in the K^oP and $\bar{K}^oP$ cross section of the order of 10^{-3} of the cross sections. Therefore the regeneration experiment which employs a simple beam and one setup is the equivalent of two experiments in which one would have had to obtain an absolute accuracy of better than 0.1%

There is the very strong possibility, arising from extrapolation of known Regge trajectories, that we shall find the cross sections differ by as much as 3% (30 times the effect we set out to measure). Gilman (SLAC PUB 401, to be published in Phys. Rev.) pointed out that measurement of the energy dependence of the regeneration would give the high energy behavior of the ω trajectory. In other words, even at 200 BeV, we may not be observing Pomeranchuk prediction for infinite energy, but we can measure whether we are approaching his prediction.

One interesting aspect is that at lower energies the regeneration in hydrogen is exceedingly difficult to observe. This is because the regeneration intensity goes with the square of the density of atoms and the effective target length. At low energies (i.e. 1 BeV) the effective target length is essentially the K_S^o decay length or a few centimeters; at high energies (i.e. 100 BeV) the decay length has become 5.4 meters so one gets the regeneration intensity which would be 10^4 greater if there were still the same difference in the K^oP and $\overline{K}^oP$ cross sections.

Theoretical Formalism, Sensitivity, and Rates

One needs to measure the interference between the $K_L^o + P \rightarrow P + K_S^o$ regeneration (leading to the decay $K_S^o \rightarrow \pi^+\pi^-$) and the CP-violating decay $K_L^o \rightarrow \pi^+\pi^-$. The number of decays into $\pi^+\pi^-$ as a function of time (or distance) is given by the expression (neglecting background)

$$\left.\begin{array}{c}\text{Number of}\\ \pi^+\pi^-\end{array}\right\} = \left| A(K_S^o) \to \pi^+\pi^- \right|^2 \cdot \left[|R|^2 e^{-\Gamma_S t} + 2|R|\,|\eta_\pm|\, e^{-(\Gamma_S + \Gamma_L)t/2} \cos(\delta m t - \Delta\phi) + |\eta_\pm|^2 e^{-\Gamma_L t} \right], \quad (1)$$

where $A(K_S^o) \to \pi^+\pi^-$ is the decay amplitude of $K_S^o \to \pi^+\pi^-$, $\Gamma_S + \Gamma_L$ are the decay constants for K_S^o and K_L^o respectively, $\eta_\pm$ is the CP-violation decay ratio of amplitudes:

$$|\eta_\pm| = \left| \frac{A(K_L^o \to \pi^+\pi^-)}{A(K_S^o \to \pi^+\pi^-)} \right| \simeq 1.9 \times 10^{-3}.$$

where $\delta m = m(K_L^o) - m(K_S^o) \approx 1/2\ \Gamma_s$, $\Delta\phi = \phi_R - \phi_{\eta_\pm}$ and if Gilman's estimate is correct $\Delta\phi \approx \pm 90^\circ$, and $R = |R| e^{i\phi_R}$ is the regeneration amplitude

$$|R| \approx \Lambda N \frac{\Delta\sigma}{2} e^{-L/2\lambda} \left| \frac{e^{-L/2\Delta} - e^{i\Delta k L}}{\frac{1}{2} - i \frac{\delta m}{\Gamma_S}} \right| ,$$

where Λ is the decay length in the laboratory for K_S^o ($\approx$ 5.5 meters for 100 BeV/c), N is number of atoms/cm^3, L is the length of the sample, λ is the interaction mean free path in the sample, and $\Delta\sigma$ is the difference in total cross sections. (Gilman expects $\Delta \mathrm{Re}\, f(0^\circ) \approx \Delta \mathrm{Im} f(0^\circ)$) so that there really should be a factor of 1.4.)

For purposes of estimating the sensitivity of the method, we set $\Delta\sigma = x$ millibarns.

For purposes of making estimates for an experiment in the range $50 \rightarrow 100$ BeV, we have used a 20 foot long hydrogen target and we get $|R| \approx x \times 10^{-2}$.

Using expression (1) and requiring that we be able to observe a 10% interference term, we obtain

$$0.1 = \frac{x \times 10^{-2}}{2 \times 10^{-3}}$$

or $x = 0.02$. Therefore, we can measure a difference of 20 microbarns between K^oP and $\bar{K}^oP$. The sensitivity of the method for determining a difference in the cross section is therefore of the order of 10^{-3}.

In order to obtain a measurement of the interference term to 10%, one should obtain about 4000 events in each Γ_S decay length (i.e. 4 bins with 1000 events each), and one should measure over 4 Γ_S decay lengths. One obtains about 4×10^{-6} $K_L^o \rightarrow \pi^+\pi^-$ decays per Γ_S decay length. Assuming an early experiment will be of the order of 10^5 pulses for two target thicknesses and a target empty run (i.e. about 12 days total running), we get

$$4 \times 10^3 \simeq \frac{\text{flux}}{\text{pulse}} \times 4 \times 10^{-6} \times 10^5 \text{ pulses.}$$

The flux per pulse is about 10^4 K_L^o per pulse in some energy interval. We choose ± 10 BeV/c at 100 BeV/c. With 10^{12} interacting protons and $\Delta\Omega = 4 \times 10^{-8}$, we can get this in a beam at 10 mrad. If the beam is at 5 mrad we only need 10^{11} protons; however, there are serious neutron background problems which are discussed in the next section. Lower energy K_L^o (40 GeV/c) are 6 to 20 times as abundant as those at 100 GeV/c.

The events of interest in a 20 GeV/c interval per pulse are given by

$$\text{Flux} \times \text{number of } \Gamma_S \text{ decay lengths} \times \text{prob of decay}/\Gamma_S$$

$$= 10^4 \times 4 \times 4 \times 10^{-6} = 0.16 \text{ events/pulse.}$$

However for the lower energy K_L^o with higher fluxes and shorter decay lengths, we get $\approx 10^5 \times (\approx 20) \times 4 \times 10^{-6} = 8$ decays/pulse. This would be reasonable for a wire spark-chamber system on line to a computer if there were no backgrounds.

Background Problem

There are neutrons as well as K_L^o in the beam. About 1/4 of the K_L^o will interact, and about 1/3 of the neutrons, to produce some K_S^o which are not coherent. For example,

$$K_L^o + P \begin{cases} \nearrow K^{o*} + P \\ \searrow \bar{K}^{o*} + P \end{cases}$$

and the $K^{o*} \rightarrow \pi^o + K^o$ which 1/3 of the time decay as $K_S^o \rightarrow \pi^+\pi^-$.

These are background events (B.G.) and the formula (1) must be revised to take account. It now becomes

$$\text{No. of } \pi^+\pi^- = |A(K_S^o \to \pi^+\pi^-)|^2 \cdot \Big[(|R|^2 + \text{B.G.}) e^{-\Gamma_S t} + 2|\eta_\pm| |R| e^{-(\Gamma_S + \Gamma_L)t/2}$$

$$\times \cos(\,mt - \Delta\phi) + |\eta_\pm|^2 e^{-\Gamma_L t} \Big]. \tag{2}$$

The presence of the B.G. term clearly shows the importance of measuring the interference oscillation and the $|\eta_\pm|^2$ term. Observing $K_S^o \to \pi^+\pi^-$ is not evidence of coherent regeneration.

If one surrounds the hydrogen target with a veto counter system, one can detect those reactions in which the B.G. K_S^o produced is accompanied by a charged particle (or recoil proton). We estimate that this is well over 90% of the time. In other reactions such as peripheral K^{o*} production in the decay of the K^{o*} the angle will lie outside the acceptable cone (2×10^{-4} radians) for coherent K_S^o regeneration about 90% of the time. If we combine these factors with the fact that only 1/4 of the K_L^o interact and only 1/3 of the K^o decay as $K_S^o \to \pi^+\pi^-$ we find that the B.G. in the energy region of interest is

$$1/4 \times 1/3 \times 0.1 \times 0.1 \times 10^4 = 8 \text{ B.G. events/pulse.}$$

All of these events are accompanied by π^o (the charged particle veto removed the others). It would be desirable to put in a set of γ-ray veto counters outside the acceptable cone of K_S^o decays, and perhaps in back of the K_S^o detecting system. We also can gain a factor of 3 by only accepting events after one Γ_S lifetime. From expression (2) we see the B.G. falls off with twice the exponential decay rate of the interference term. There will be a more prolific background of lower energy events due to the higher flux at low energies. A hodoscope which selects a range of fixed opening angles would reduce the false triggers.

The neutron production of K_S^o can be a much more serious background. We have used the Hagedorn-Ranft curves for neutron (proton) in the beam and for K_S^o (K^+ production) at 0°, to estimate the production of K_S^o. In a 5 mrad neutral beam there are 100 times more neutrons above 140 BeV than in a 10 mrad beam, and there are 20 times more with energies above 120 BeV/c for the same number of interacting protons. However, one needs 10 times as many interacting protons in a 10 mrad as a 5 mrad beam. One is still in serious trouble due to those above 140 BeV which produce K^o's with energies above 60 BeV. Specifically about 140 K^o's will be produced in a beam with 10^4 K_L^o at 100 ± 10 GeV. We have integrated the production of K^o above 60 BeV and after correcting for the fraction that decay and the effect of the veto system we have a B.G. that is about 20 times our signal in the 5 mrad neutral beam. In the 10 mrad beam the B.G. is only about 5 times our signal. (If the same number of interacting protons were used the factor between the two beams is about 40/1 in background events.)

We therefore feel a 10 mrad beam is the more desirable neutral beam.

To evaluate the background it is very desirable to run with two hydrogen targets; one should be 1/2 or 1/3 the length of the other, i.e. 10 feet or 7 feet.

In expression (2) the B.G. term will vary essentially linearly with target length whereas the R^2 term goes as the square of the length. The interference term goes linearly with the length. Therefore two lengths of target will allow us to evaluate the B.G. term experimentally.

Experimental Apparatus

Although the summary report of J. H. Smith has the experimental layout immediately beyond the muon shield at about 400 feet, it could be further away. The beam intensity of 10^{12} protons interacting could be raised with an accompanying decrease in solid angle from the 4×10^{-8} steradians specified.

The coherent regeneration is precisely in the direction of the original beam. The opening angle for $K_S^o \to \pi^+\pi^-$ for 100 BeV is slightly less than 9 mrad. The decay region is about 80 feet and the wire spark chambers are about 20 feet apart. (The setup is very similar to that described by J. H. Smith for $\pi^- + P \to K^o + \Lambda$ production studies -- see C.1-68-18.) The size of the magnet needed is set by the largest angle of one pion, namely about 8 mrad times the furthest decay distance, namely 100 feet, which gives 0.8 feet. Therefore, the Smith magnet with 2 ft $\times$ 2 ft aperture is satisfactory for this experiment also.